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Experimental and computational investigations of thermal modal parameters for a plate-structure under 1200 °C high temperature environment

Dafang Wu *, Yuewu Wang, Lan Shang, Huaitao Wang, Ying Pu

School of Aeronautic Science and Engineering, Beijing University of Aeronautics and Astronautics, Beijing 100191, China

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ABSTRACT

When a hypersonic aircraft flies at a high Mach number, the plate-like attitude control structures, such as the wings and rudders, will be exposed to an extremely high-temperature environment. To obtain the thermal modal parameters of a structure that are difficult to measure, a high-temperature transient heating test system and a vibration test system were combined to establish a test system that can perform the thermal/vibration test at 1200 °C. Infrared radiation heating was employed to generate a controlled time-varying high-temperature environment, and an exciter was used to exert vibration excitation on the free end of the cantilever rectangular plate. A self-developed extension configuration of a high-temperature-resistant ceramic pole was used to transfer the vibration signals of the structure to a non-high temperature zone, and the acceleration sensors were applied to identify the vibration signals. The test data were analyzed using a time-frequency joint analysis technique, and next, the key vibration characteristic parameters of structure in a thermal-vibration coupled environment up to 1200 °C (e.g., the modal frequency and modal vibration shape) were experimentally obtained. In addition, the numerical simulation on the thermal modal characteristics of a rectangular plate was performed. The calculated results coincide favorably with the test results, verifying the credibility and effectiveness of the experimental methods. The research results can provide an important basis for the dynamic performance analysis and safety design of structure under high-temperature thermal-vibration conditions for hypersonic flight vehicles.

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1. Introduction

Hypersonic flight vehicles can fly at a high speed exceeding Mach number of 5 ($Ma > 5$); at such high speeds, the thermal environments generated by the aerodynamic heating will be notably harsh. The temperatures of the thermal environments exerted on the attitude control structures, such as the wings and rudders, generally exceed 1000 °C [1]; the temperatures at the hypersonic aircraft's wing leading edge and nose cone are even higher. Moreover, during a long flight, the attitude control structures (e.g., wings and rudders) for long-range, high-speed flight vehicles undergo prolonged serious vibration. The high temperature caused by aerodynamic heating changes the mechanical properties of the materials and structures, leading to changes in the vibration characteristics of the wings and rudder. These changes have significant impacts on the flutter characteristics and controllability of long-range, high-speed flight vehicles. Therefore, studying the variation of the modal frequencies and other dynamic parameters of the wings and rudders versus temperature under a force-heat-coupled environment is significant for the reliability design and flight safety of hypersonic flight vehicles.

Currently, numerous scholars have theoretically analyzed and numerically calculated the vibration properties of structures in the thermal environment. Shen et al. [2] calculated the modal frequency of doubly curved functionally graded composite panel in high temperature based on a nonlinear modeling. Niu et al. [3] dealt with the nonlinear thermal flutter problem of a supersonic composite laminated panel by using the differential quadrature method (DQM). Brown [4] performed a theoretical analysis and numerical calculations of the natural frequency and vibration modes of the composite nozzles of an X-34 FASTRAC rocket in a high-temperature environment. Lei et al. [5] used the element-free *kp*-Ritz method to carry out a free vibration analysis on functionally graded composite plates reinforced by single-walled carbon nanotubes (SWCNTs) in thermal environment. The theory

* Corresponding author.
E-mail address: wdf1950@163.com (D. Wu).

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must be based on experimental data, and the calculated results need to be verified by the experiment; therefore, it is very significant to obtain the vibration performance of structures in severe high-temperature environments via experiments.

In 1955, Vosteen et al. from the Langley Aeronautical Laboratory of NACA [6,7] experimentally studied the vibration performances of a simple wing structure subjected to non-uniform temperature loads, and the highest temperature in Vosteen's research was 139 °C. In 1960, McWithey et al. from the Langley Research Center [8] performed experimental research on the vibration characteristics of the X-15 wing in thermal environments, and the temperature on most of the area of the wing was less than 347 °C. In 1991, Kehoe [9,10] used the laser vibrometer to measure the modal frequencies and modal shapes of a plate structure under thermal environment with temperature of 245 °C. In recent years, with the continuous improvement of the design speed of hypersonic aircraft, the thermal environment exposed on the aircraft's outer surface became increasingly harsh; as a result, the design department has been urgently seeking the thermal modal parameters of structures based on a test method under even higher temperatures. In 2010, at the NASA Dryden flight research center (DFRC), high-temperature acceleration sensors were used in the thermal-vibration test for a C/SiC rudder of an X-37 [11]. The high-temperature acceleration sensor has the advantages of being conveniently installed and the ability to directly measure the vibration signals of the measuring point. Because of the difficulty in manufacture, only a few companies can manufacture the acceleration sensor which is applicable in the extremely high temperature. It is noted that the nominal working temperature of the high temperature acceleration sensors produced by the PCB Piezotronics, Inc and the Meggitt's Endevco Corporation can reach up to 760 °C; however, because the working temperature range is wide for the high temperature acceleration sensors, the measured results at different temperature ranges must be corrected, and their accuracies are influenced significantly by the temperature of the environment. Therefore, the thermal modal parameters in the test of NASA DFRC, in which the high temperature acceleration sensors were used, were only measured under a thermal environment as high as 482 °C. In fact, the temperature on the wing surface of X-37 is far higher than 482 °C, suggesting that the new acceleration sensor with higher working temperature or other test method must be developed to improve the test temperature in the thermal vibration joint test. In 2011, the researchers from Agency for Defense Development of Korea and Chungnam National University used a non-contact method based on a laser vibration measuring technique to perform a thermal modal test for a rectangular plate, and the experimental temperature reached up to 500 °C [12]. In 2015, engineers from the Beijing Institute of Structure and Environment Engineering used a laser scanning vibrometer to perform a thermal modal parameter survey on flat and stiffened plates and obtained the thermal modal parameters of plates at 500 °C [13]. In Refs. [12,13], to avoid interference with the laser beam by the heating source, only one side of the plate was heated in the experiments, and the un-heated side was used to acquire the vibration signals. Such conditions were different from the practical thermal conditions for the hypersonic aircraft, in which both surfaces of the wings and rudders were heated simultaneously. In fact, heating both sides of the specimen is much more difficult than heating only one side in the thermal modal test. That is because if both sides of the specimen are heated in the test, the laser beam has to travel through the infrared heating arrays before arriving at the specimen's surface; also, the laser beam has to travel through the infrared heating array again before reflecting back to the target surface of acquisition instrument. In the heating process, the temperature of the infrared radiation source is higher than that of specimen's surface, and the light generated by the heating arrays will cause strong interference with the transmitting of the effective information from the specimen, the higher the temperature, the stronger the interference. Although heating only one side of the specimen and acquiring the vibration signals on the un-heated side can avoid the interference caused by the heating source, this method cannot realize the real thermal boundary conditions exerted on the wings and rudders of the aircraft in the flight process. If both sides of the specimen are heated in the thermal modal test, the problem of interference to the laser beam caused by high temperature infrared radiation lights has to be resolved. Moreover, some thermal vibration joint tests at the temperature of 500 °C have been reported [14–16].

Overall, it can be concluded from the existed literatures that the realized temperatures in the thermal modal tests were approximately 500 °C. Therefore, it is a challenging task to improve substantially the test temperature and accomplish the measurements of vibration parameters of the wings and rudders of hypersonic aircraft under extremely high temperature environment up to 1200 °C. The authors have performed researches on the experimental method of thermal modal up to 500 °C in recent years [17], but have not presented the comparison and verification between the experimental and numerical results. In fact, the reciprocal support and verification between the numerical and test results is highly important for the credibility and effectiveness of the test technique; up to now, the research of the thermal modal test at extremely high temperature of 1200 °C as well as its comparison with the numerical results has not been reported.

In this paper, a transient aerodynamic heating simulation system and a vibration test setup are combined to establish a thermal-vibration test system that is able to perform the thermal vibration test at 1200 °C. Infrared radiation heating arrays are used to generate a controlled thermal environment and simultaneously heat both sides of the plate, while an exciter continuously excites the plate specimen at its free end. A specified high-temperature extension configuration is designed and used to transfer the vibration signals to a non-high-temperature zone, and the ordinary acceleration sensors are employed to measure the important dynamic characteristic parameters, such as the frequencies and modal shape, for the rectangular plate at 1200 °C. Moreover, the thermal modal parameters of the rectangular plate are calculated in the present work, and a comparison between the numerical result and the test result is performed, verifying the credibility and effectiveness of the proposed test method.

The authors of the present work have established a thermo-mechanical joint test system that can perform fracture performance tests under an extremely high temperature oxidation environment up to 1500 °C [18]. In the thermo-mechanical test, a U-shaped water-cooling pipe was designed in the metal loading rod. By controlling the amount and rate of the cooling medium through the pipe, local part of the loading connector was cooled, which ensured that the metal connectors were able to work in 1500 °C safely. Key performance parameters, such as the fracture strength and time to failure of high-temperature-resistant C/SiC composite structure, were tested and measured in oxidation environments up to 1500 °C. However, for the thermal modal test, in order to obtain the thermal modal information of the rectangular plate, some vibration signal extension devices need to be installed in the different cross sections of the plate, and the mass of the extension device should be as small as possible to reduce the effect of additional mass on the vibration characteristics of the test specimen. Therefore, the metal extension device is unsuitable in the thermal modal test; it is not only because the metal extension device has large mass, but it also will soften in high temperature, which results in fidelity loss of modal information transmitted from the surface of the plate. If a water cooling apparatus is installed in the extension device, the additional mass on the

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